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THE FERMENTATION OF SLUDGE FROM MUNICIPAL SEWAGE IN SLUDGE DIGESTERS

(Sbrazhivaniye osadkov gorodskikh stochnykh vod v metantenkakh)

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THE FERMENTATION OF SLUDGE FROM MUNICIPAL SEWAGE IN SLUDGE DIGESTERS

L. I. Giunter, G. N. Lutsenko

At present, anaerobic fermentation in sludge digesters is the basic method for the treatment of sludge in municipal sewage. There has been a tendency in recent years to turn to new methods, such as the direct mechanical dehydration of raw sludge, aerobic stabilization, wet combustion, etc. These new methods continue to call into question the efficiency of sludge digesters as a means of sewage treatments.

The operation of sludge digesters in the USSR and abroad has been somewhat varied, particularly with respect to thermophilic fermentation and multistage sludge digesters. In view of this it would appear worthwhile to examine the information accumulated in studies of the fermentation process and the operation of sludge digesters. This makes it possible to determine with the aid of technical and economic calculations the efficiency of sludge fermentation and obtain a firm basis for selecting the optimal working conditions of sludge digesters.

Anaerobic methane fermentation is a complex biochemical process based on the ability of microorganisms to naturally oxidize organic materials contained in the sludge of wastewaters. The basic components of the organic materials found in sludge from primary settling tanks are carbohydrates, fats and proteins, constituting 80-85% of the organic materials (15-20% carbohydrates, 20-30% fats, 20-30% protein). Besides sludge, excess activated sludge (whose organic mass is about 50% protein) is subjected to fermentation in sludge digesters.

It is known that the decomposition of the organic materials in

sludge digesters occurs in two phases: in phase I, known as the acid or hydrogen fermentation phase, fatty acids, hydrogen, CO_2, NH_3, alcohols, amino acids, H_2S, glycerin, etc. are formed by common saprophytic bacteria out of the initial organic materials. Sludge entering the sludge digester already contains a great many of these bacteria. One milliliter of sludge with a moisture content of 95% contains 10^8 bacteria which break down proteins, 5×10^7 bacteria which break down starch and 10^9 which attack cellulose [5].

Phase II -- alkaline or methane fermentation -- is accomplished by methane bacteria which, unlike the bacteria of phase I, do not form spores and grow under strictly anaerobic conditions and in a weakly alkaline medium in the presence of substrates -- products of phase I suitable for use. It should be borne in mind that raw sludge contains an insignificant number of methane bacteria (50-500 per gram of sludge with a 95% moisture content).

One of the natural characteristics of methane bacteria is their ability to reduce carbon dioxide with hydrogen:

$$CO_2 + 4H^+ = CH_4 + 2O^- + \text{energy}.$$

The hydrogen donor may be any substrate capable of producing it (alcohols, fatty acids, etc.).

Besides carbon dioxide, methane bacteria are needed in ammonium salts as a nitrogen source.

The question of the chemical mechanism by which methane is formed from phase I fermentation products is still unclear. Studies employing labeled atoms (C^{14}) [22] have shown that about 70% of the methane is formed by the decarboxylation of acetic acid and only 30% by the reduction of CO_2 (Fig. 1).

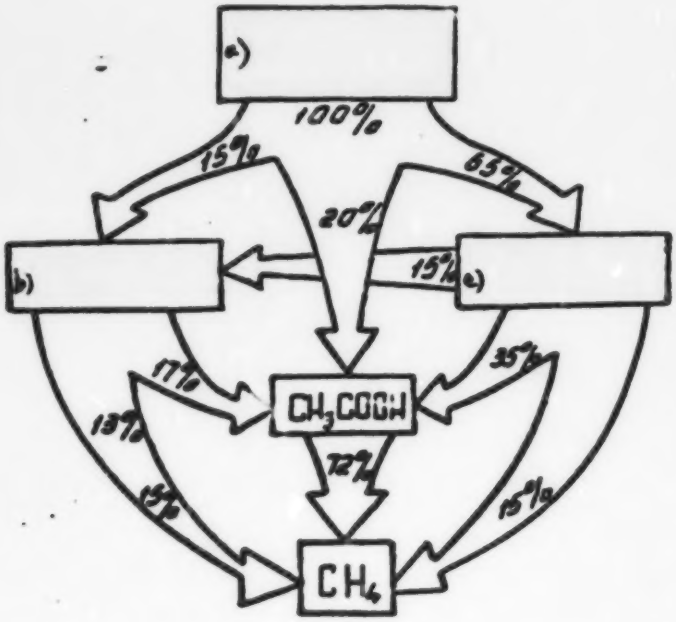

Fig. 1: Schematic diagram of the formation of methane.

Key: a - organic material
b - propionic acid
c - intermediate products

The anaerobic fermentation of organic material is characterized by a significantly smaller growth of the bacterial mass than the aerobic process, which is one of its advantages.

It is known that methane bacteria are sensitive to pH (optimal pH = 7.5-8.5). Normally anaerobic fermentation constitutes an equilibrium system in which the rate of the formation of organic acids is equal to or less than the rate of methane formation at a level of alkalinity sufficient for acid neutralization.

An unbalancing of the system, brought on by such unfavorable conditions as an increase in the charge dose, a drop in temperature or the introduction of toxic substances, leads to a disturbance of the process.

The most frequent cause of a disturbance of the fermentation process is a sharp increase in the load of organic material exceeding the ability of the bacterial mass to assimilate it. At the same

time, acid-forming bacteria, which are more resistant to unfavorable conditions (change in pH, temperature, the accumulation of exchange products, etc.) and which have a much higher growth rate than the methane-forming bacteria, adapt very rapidly to the increased load by simply increasing the number of bacteria which metabolize the organic material. The methane-forming bacteria reproduce quite slowly: their reproduction period is on the order of several days [16]. Consequently they cannot adapt to an excess load of organic material before the pH has been reduced to a toxic level due to a quantity of organic acids exceeding the ability of the system to neutralize it.

The usual means of eliminating this type of disturbance is to reduce the organic load or even discontinue the addition of raw sludge into the sludge digester for a short time.

Another method which has been proposed by which lime is added to the sludge digester in order to increase the alkalinity of the system; at a high level of alkalinity an increase in the concentration of organic acids does not have a detrimental effect on the methane-forming bacteria [20].

The third and newest method of preventing a disturbance of equilibrium between the methane-forming and acid-forming bacteria consists in artificially controlling the population of methane-forming bacteria by returning to the sludge digester a portion of the solid phase of the discharged fermented sludge [18].

The methane fermentation of the organic material in sludge leads to the formation of gaseous fermentation products consisting essentially of methane (65-70%) and CO_2. As studies by the AKKh [Academy of Municipal Engineering] [3] have shown, the yield of gas during the

fermentation of sludge is determined solely by the decomposition of fats, proteins and carbohydrates; the other organic materials in the sludge (about 15%) do not contribute to the formation of gas. Only gaseous end products are formed by the decomposition of fats and carbohydrates; during the decomposition of proteins, some of the end products pass into the muddy liquid. Consequently the decomposition of 1 gram of protein material liberates less gas than the decomposition of fats and carbohydrates: the gas yield from 1 g protein is 0.71 g; 1 g carbohydrate, 0.985 g; 1 g fat, 1.31 g [21]. Since activated sludge consists primarily of proteins, less gas is yielded by its fermentation than by the fermentation of raw sludge.

Even with an infinitely large fermentation time, the organic material in sludge is never completely decomposed in sludge digesters. For each of the basic components of the organic material, as well as for the sludge itself, there exists a so-called fermentation limit (α, %) which is determined according to the following formula:

$$\alpha = (x \cdot 0.7 \cdot 1.31) + (y \cdot 0.625 \cdot 0.985) + (z \cdot 0.48 \cdot 0.71) \cdot 100, \quad (1)$$

where x, y and z = the respective content of fats, carbohydrates and proteins in 1 g of ash-free material;

0.7; 0.625; 0.48 = the fermentation limits of these components in fractions of a gram, determined experimentally;

1.31; 0.985; 0.71 = Roediger's coefficients.

The content of these components in the sludge of different treatment plants depends on the composition of the wastewater; thus the decomposition of 1 g ash-free material is accompanied by the liberation of a non-uniform quantity of gas, and consequently the

specific decomposition of ash-free material in the sludge may vary.

The Table gives the results of a determination of the fermentation limit and the maximum possible gas yield from 1 g ash-free material in sludge taken from several treatment plants in Moscow and other cities. The results of these studies have shown that the chemical composition of the ash-free material and its fermentation limit must be taken into account in the design and operation of sludge digesters, and that the technical fermentation limit cannot be assigned, since it is dependent solely on the chemical composition of the ash-free material in the sludge and varies over a very wide range, particularly when industrial sewage is introduced into municipal sewer systems.

Besides the chemical composition of the sludge, the liberation of gas and the degree of decomposition of the ash-free material are significantly influenced by temperature, by the daily charge dose in the sludge digester, by the moisture content of the sludge, as well as by the possible presence of toxic substances which inhibit the fermentation process.

Experimental work by the AKKh [1, 2, 3] has shown that the decomposition of the ash-free material in sludge y changes as a function of the daily charge dose of the sludge digester d according to the equation:

$$y = a - nd$$

where n is the tangent of the slope angle of the straight line and is dependent on the fermentation temperature and the moisture content of the sludge.

The linear dependence does not hold true at high charge doses, which may be termed the maximum loads for sludge digesters. The maximum loads vary widely depending on the fermentation temperature: d_{max} is

Fermentation Limit of Sludge and Max. Gas Yield Based On Data Gathered in 1962-1964

City, treatment plant	α, %	Max. gas yield, mg/l ash-free material
Moscow		
Lyublinsk aeration plant:		
raw sludge	52-54	556
mixture of raw sludge and activated sludge in 1:1 ratio by ash-free material	46-48	452
Kur'yanovsk aeration plant:		
raw sludge	54-56	572
Kuntsevsk aeration plant:		
raw sludge	44-46	463
Tushinsk aeration plant:		
raw sludge	51	535
activated sludge	41-43	442
mixture of raw sludge and activated sludge in 1:1.5 ratio by ash-free material	45-46	478
Chelyabinsk		
raw sludge	60.9	580
Ivanovo		
raw sludge	41.4	393
Kalinin		
raw sludge	40.0	420
Yaroslavl		
raw sludge	36.6	350
Kharkov		
raw sludge	53.8	513

equal to 12% at 28° C (93-94% moisture content of sludge), 16% at 32° C, 24% at 53-55° C.

The insignificant difference in the decomposition of ash-free material with low charge doses at different fermentation temperatures is evidence for the effectiveness of employing a thermophilic regime in this case (Fig. 2). Conversely, at high charge doses with thermophilic fermentation (t = 53° C) the capacities of sludge digesters are reduced by 50% compared with mesophilic fermentation (t = 32°). The very same degree of decomposition, 45% for example, can be attained under different conditions of sludge digester operation: t = 28° C, d = 6%; t = 32-36° C, d = 8%; t = 51° C, d = 15%; t = 53-55° C, d = 20%.

In the fermentation of a mixture of sludge and activated sludge, the technological parameters of the sludge digesters must be different. It is clear that in the fermentation of an activated sludge with α = 42-43% and of raw sludge similar to that of the Kuznets aeration plant and sludge, decomposition cannot be achieved.

By constructing similar graphs at the design stage, and later the operating stage, of sludge digesters, it will be possible to make a well-founded choice and calculation of sludge-digester parameters, and to monitor their operation.

In recent years the wide-spread use, both private and industrial, of synthetic surface-active substances has led to a sharp rise in the concentration of surfactants in wastewater. Adsorbed on materials suspended in sewage liquid, surfactants are introduced into sludge digesters with the sludge. It has been determined by studies in the USSR and abroad that the inhibiting effect of surfactants on the fermentation of sludge results in a reduced yield of fermentation gas, the exact degree depending on the type of surfactant and its concentration

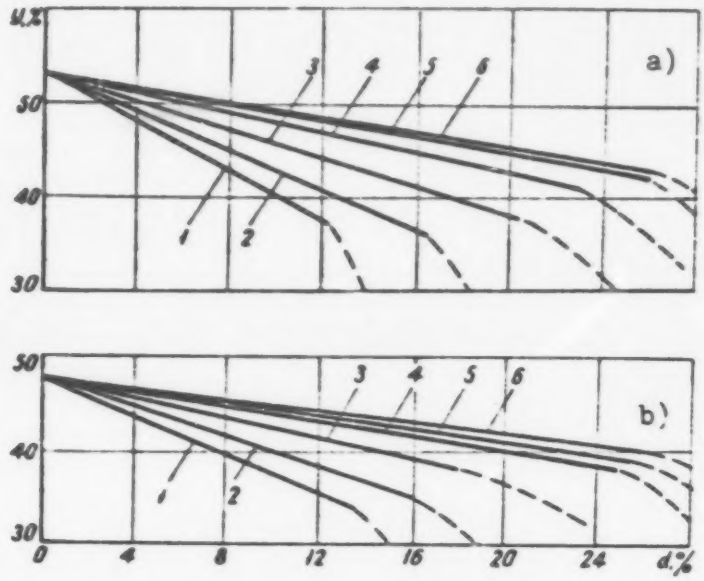

Fig. 2: The decomposition y of the ash-free material in sludge as a function of the charge dose d and the fermentation temperature t.

Key: a - sludge from primary setting tanks (93% moisture content); b - mixture of sludge and activated sludge in a 1:1 ratio in terms of ash-free material (95% moisture content); t, °C: 1 - 28; 2 - 32-36; 3 - 49; 4 - 51; 5 - 53; 6 - 55.

[8, 19]. According to data obtained by the Academy of Municipal Engineering, the unfavorable influence of surface-active substances on sludge fermentation under mesophilic and thermophilic conditions is reflected in a lower gas yield, a reduction in the degree of decomposition of ash-free material, and a change in the proportion of gas liberated by fats, proteins and carbohydrates. The reason for the inhibiting influence of surfactants on fermentation lies in their biochemical stability and their ability to be adsorbed at phase boundaries, which tends to limit the fermentative hydrolysis of fats, carbohydrates and proteins as well as retard the activity of methane-forming bacteria when present in sufficient concentrations. This

retardation is accompanied by the build-up of organic acids in the sludgy liquid and a reduction of CH_4 in the gas [6, 7].

The extent of the inhibiting effect of surfactants and their mixtures on the fermentation process is dependent not only on the concentration of these substances in the sludge, but also on the charge dose of the sludge digester. There is an increase in this effect as 1) the concentration of surfactants in the sludge increases and 2) while the content of surfactants in the sludge is kept constant. (Fig. 3, 4).

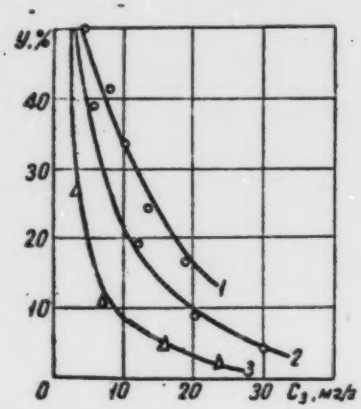

Fig. 3: Decomposition of ash-free material as a function of the content of surfactants in the sludge.

Key: 1 - mixture of surfactants (sulfonol NP-1: sulfonol NP-3: sulfonol chloride: alkylsulfate = 1:1:1:1), t = 53° C, d = 12%; 2 - sulfonol NP-3, t = 32° C, d = 6%; 3 = sulfonol NP-3, t = 53° C, d = 12%.

Under practical conditions it is advisable to monitor the load of surfactants in the sludge digester, since the load depends on the initial concentration of surfactants in the sludge and the daily charge dose:

$$q = [C_z (100 - P_z) d] /10 \qquad (3)$$

where q = load, r/m^3/day;

C_z = concentration of surfactants, mg/g;

P_z = moisture content of sludge in digester, %.

An analysis of the results of our investigations shows that a minimum 35% decomposition of the ash-free material in sludge can be

ensured in mesophilic and thermophilic fermentation by adhering to a specific surfactant load in the sludge digester. For surfactants with a slight inhibiting effect (sulfonol chloride, alkylsulfate), the maximum load is 85 r/m^3/day; for surfactants with a strong inhibiting effect (sulfonol NP-1, sulfonol NP-3), 40 g/m^3/day (Fig. 5.). At these loads the yield of gas is 20-25% less than the value calculated according to formula (2), and the heating value of the gas is diminished by approximately 10%.

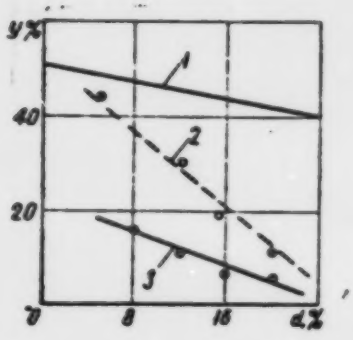

Fig. 4: Decomposition of ash-free material as a function of the daily charge dose of raw sludge (53°C).

Key: 1 - theoretical dependence for sludge from Tushinsk aeration plant (y = 51.0 — 0.45 d); 2 - actual dependence for content of 11 mg/g surfactant mixture in sludge (sulfonyl NP-1:sulfonyl NP-3:sulfonyl chloride:alkylsulfate = 1:1:1:1); 3 - as above, with content of 6.3 mg/g sulfonyl NP-3 in sludge.

In order to adhere to the maximum loads at a surfactant concentration of about 10 mg/g in the sludge in accordance with expression (3), the charge doses recommended in the SNP [Construction Specifications and Regulations] must be reduced by a factor of 1.2-1.3 in the mesophilic regime and 2.5-3.0 in the thermophilic regime for substances which strongly inhibit the process, and by a factor of 1.1-1.5 in the thermophilic regime for substances which weakly inhibit fermentation.

Substances which strongly inhibit the fermentation of sludge include the biochemically non-oxidizable alkylbenzenesulfonates obtained from propylene tetramers and the straight-chain alkylbenzenesulfonates, which undergo biochemical oxidation under aerobic con-

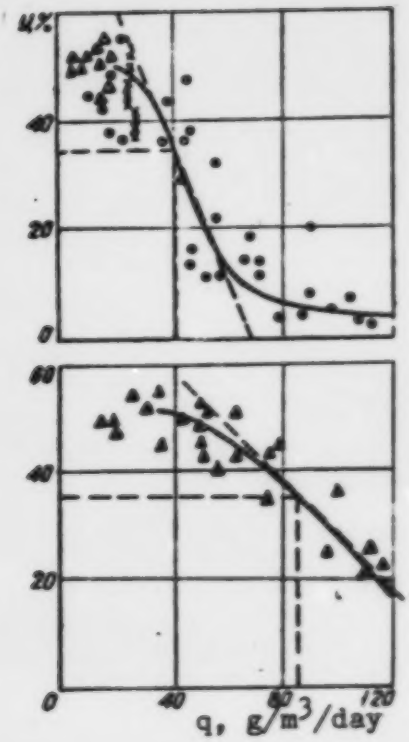

Fig. 5

Fig. 5: Change in ash-free sludge decomposition as a function of the surfactant load in sludge digesters:

Key: o - NP-1 sulfonol, NP-3 sulfonol, mixture III (t = 32, 53°C; △ - control; x - Lyuberetskiye sludge digesters (April, May, June 1966); ▲ - alkyl-sulfate, sulfonol chloride, Mixture I, I (t = 32, 53°C)

ditions to a satisfactory degree. Thus, even if only biochemically oxidizable surfactants were used in the national economy, their presence in the sludge of wastewater would have an inhibiting effect on fermentation.

These circumstances require that a determination be made of the concentration of surfactants in sludge, and of the calculated (during the design stage) and actual (during operation) surfactant loads in sludge digesters. In cases in which the surfactant loads prove to be lower than the maximum value mentioned earlier, the surfactants will have no effect on the operation of the sludge digester, and calculations can be made according to the original equations [1, 2]. But if the surfactant load is found to exceed the tolerance, the daily charge doses should be reduced according to the formula:

$$d = \frac{10q}{C_z(100 - P_z)} \qquad (4)$$

An analysis of the results obtained shows that an increase in the introduction of surfactants into sewer systems has a particularly detrimental effect on sludge digesters operating in the thermophilic regime, since a rise in the fermentation temperature does not lead to an appreciable increase in the decomposition rate of the surfactants, and, consequently, the necessary sludge-digester volume will increase and will be the same for both the mesophilic and thermophilic regimes.

In a number of foreign countries (Great Britain, United States, West Germany) the operation of sludge digesters is being disrupted even at relatively low charge doses (3-5%), a result of the high content of surfactants in the sludge (up to 15 mg/g dry material).

English scientists are currently working on a means of preventing surfactants from inhibiting the fermentation of sludge. One proposal is the introduction of quaternary ammonium compounds into the sewage before it reaches the primary settling tanks; these compounds would react with the anions of the surfactants to form complex compounds which would not interfere with the fermentation of the organic constituents of the sludge [17].

Besides surfactants, materials such as copper, chromium, zinc, nickel and formaldehyde can have a toxic effect on processes in sludge digesters. It has been determined that the presence of copper in the sludge in a concentration higher than 30 mg/l, of chromium (VI) higher than 6 mg/l, of chromium (III) higher than 50 mg/l, or of lead higher than 70 mg/l leads to a significant retardation of the fermentation process [13].

It appears that the toxicity level of heavy metals can be effectively reduced by the addition of sulfides to the fermenting sludge. Most frequently used are the sodium sulfide (Na_2S) or the sulfides of aluminum, iron, etc., whose sulfate group is converted into a sulfide group under anaerobic conditions. The sulfides react with copper, cadmium, nickel, manganese, lead, arsenic, mercury, etc. to form insoluble compounds. If the sulfide is present in the sludge in a slight excess, the concentration of the soluble ions of all these metals will fall below 0.001 mg/l [14].

In addition to heavy metals, ordinary cations can lead to a disruption of fermentation. Studies have shown that NH_4, K, Na, Mg, and Ca are toxic in the order given [15]. A disruption of the fermentation process occurring as a result of the introduction of such substances into the sludge digester can be overcome by diluting the

sludge. In many cases, such as a load of sodium salts, the toxicity can be eliminated by the addition of antagonistic ions (e.g., Ca and Mg).

In practice, two basic temperature ranges are employed in methane fermentation: the mesophilic (28-37%) and the thermophilic (49-55%). Other countries rely primarily on mesophilic fermentation, while in the USSR there is a growing preference for the thermophilic process. Multistage sludge digesters are widely used abroad.

The basic advantage of mesophilic fermentation is, as a rule, that the process is provided with heat by the fermentation gases. As a result of the low speed of the process a high degree of decomposition can be obtained at low charge doses (2-4%). At treatment plants in the USSR (Lyublinsk aeration plant, etc.), mesophilic sludge digesters are operated steadily with higher loads (9-11% by volume), yielding a 30-35% decomposition of ash-free material. Methane fermentation cannot render sewage residue completely harmless from a sanitary point of view.

In the USSR and abroad experiments are being conducted in an effort to intensify the process of mesophilic fermentation by charging the sludge digester with concentrated sludge, providing constant agitation, reducing the intervals between loadings, preliminary heating of the raw sludge and infesting it with microorganisms from fermented sludge, and employing a pear-shaped sludge digesting tank in order to eliminate the formation of "dead" zones, areas of sand accumulation, etc.

Particularly promising is the idea of intensifying the operation of the sludge digester by the introduction of compressed fermentation or flue gases rich in carbon dioxide [9].

But the simplest method of intensifying the process of methane fermentation is simply to conduct the fermentation in a thermophilic regime. Advantages of this method are the high fermentation rate (and the resulting reduction in the volume of the sludge digester) as well as the complete de-worming of the sludge.

The sludge digesters of the Kur'yanovsk aeration plant have been operating steadily in a thermophilic regime with charge doses of 15-18% since 1960. A decomposition of ash-free material of up to 40-42% has been achieved. Thermophilic fermentation is also employed at the Lyubertsy aeration plant.

Thermophilic fermentation does have certain basic disadvantages, however, consisting in the poor dehydration of the fermented sludge and the low quantity of heat provided by the fermentation gases. Academy studies [10] have revealed that the specific filtration resistance of thermophilically fermented sludge is 1.5 times greater than that of mesophilically fermented sludge. For this reason a more complex preliminary treatment of fermented sludge is required before dehydration by means of vacuum filters. The natural drying of sludge fermented by the thermophilic process is also hindered by its poor water loss.

Academy studies [4] have also shown that thermophilic fermentation with $t = 53^{\circ}C$ can be provided with heat by the combustion of fermentation gases only in the fermentation of sludge from primary settling tanks with a moisture content up to 94.5-95%. In the thermophilic fermentation of a 1:1.7 (by volume) mixture of sludge and activated sludge — which is typical of municipal aeration plants — the sludge digester must be supplied during the winter with an additional 15-20% heat.

The disadvantages of thermophilic fermentation outlined here have led many foreign countries to reject this process. In the opinion of foreign experts, the monetary gain resulting from the construction of thermophilic sludge digesters is offset by the greater expenditures required in dehydrating the fermented sludge. The de-worming of the sludge after mesophilic fermentation can, in the case of mechanical sludge dehydration, be achieved with the aid of special de-worming chambers [11].

In an effort to reduce the volume of the fermented sludge and reduce the size of dehydration facilities, many foreign countries are turning to multistage sludge digesters based on a two-stage fermentation process: 1) intensive fermentation of organic materials in the sludge, accompanied by the turbulent evolution of gases and the mixing of the entire sludge layer; 2) attenuation of the gas-liberation process, settling of the fermented sludge to the bottom of the tank, the formation of a layer of muddy water.

These stages are not separated in single-stage digesters. In 2-stage or multistage sludge digesters, fermentation occurs in the first stage and the separation of muddy water in the successive stage(s).

Studies conducted by the Academy [2] have shown that multistage fermentation does not improve the yield of gas or the degree of decomposition of the ash-free material in the sludge in comparison with single-stage fermentation, the volumes of the sludge digesters being equal. In 2- and 3-stage sludge digesters with a total sludge residence time of 25-30 days the volume of fermented sludge can be reduced by a factor of 2 or more. Multistage fermentation is desirable only in the first stage of the mesophilic process and a charge dose of

10-12%. Thermophilically fermented sludge is not separated in the second stage; this was confirmed by experiences at the Kur'yanovsk aeration plant [12]. In the second stage, open, unheated concrete or earthen tanks may be used.

Multistage fermentation also ensures a more stable process when the introduction of sewage into the treatment facilities is irregular, or if the sewage contains toxic substances.

Conclusions

1. A number of methods have been developed for intensifying the process of methane fermentation, including the implementation of a thermophilic operating regime, charging the sludge digesters with concentrated sludge combined with continuous mixing, reducing the intervals between loadings, introducing compressed fermentation or flue gases rich in carbon dioxide, and multistage fermentation. The decision to adopt a particular method must be based on local conditions, the subsequent utilization of the sludge, and the properties of the initial sludge, notably its chemical composition and capacity for dehydration.

2. A preliminary chemical analysis of the sludge, a calculation of the fermentation limit based on this analysis, the plotting of theoretical fermentation curves for various temperatures, and a determination of the concentration of surfactants in the sludge and the capacity of the sludge for dehydration (according to its specific resistance to filtering) make it possible to define and select the optimal operating regime of sludge digesters, and in some cases to reject the use of this method of sludge treatment.

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